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Fixed bed gasification of dairy biomass with enriched air mixture

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ABSTRACT

Concerns over the depletion of fossil fuels and global warming have increased the need for alternative–renewable energy sources. Biomass is one of the renewable and nonconventional energy sources and it also includes municipal solid wastes and animal wastes. Concentrated animal feeding operations produce large quantity of dairy biomass which might result in land and water pollution if left untreated. Different methods are employed to extract the available energy from the dairy biomass which includes co-firing and gasification. Earlier studies on gasification of dairy manure with different steam fuel ratios resulted in increased production of hydrogen. However, the gas mixture has low heat value due to large amount of diluent nitrogen. In order to enhance gas heat values, dairy biomass was gasified in a medium with enriched oxygen varying from 24% to 28% oxygen on volume basis. The effect of enriched air mixture, equivalence ratio and steam fuel ratio on the performance of fixed bed gasifier was studied. Limited studies were done using a mixture of carbon dioxide and oxygen as the gasification medium in order to explore the possibility of complete separation of CO_2 and increase the heating value of gas mixture. The results show that the peak temperature and carbon dioxide production increases with corresponding decrease in carbon monoxide with increase in oxygen concentration in the incoming gasification medium. Higher heating value (HHV) of the gases decreases with increase in equivalence ratio (decrease in oxygen concentration). The gases produced using carbon dioxide and oxygen mixture had a higher HHV when compared to that of air and enriched air gasification.

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1. Introduction

With the world energy consumption projected to increase in the upcoming years and concerns about fossil fuel depletion led to the need for nonconventional energy sources. It has been observed that the developing countries consume and need more energy. Considering these factors, efforts are being directed to identify potential alternative energy sources and the ways to improve the efficiency of conventional energy generation techniques. Different alternative energy sources identified and employed for power generation include geothermal, wind, hydropower, solar, tidal, fuel cells and biomass. Of these sources, biomass is one of the sources available for energy extraction. The word biomass not only includes wood, but also agricultural, municipal and animal solid wastes. Large concentrated animal feeding operations (CAFOs) in USA results in production of huge amount of dairy and feedlot biomass. Proper storage and disposal of this biomass is necessary or otherwise it will result in land and water pollution. Methods available for energy extraction from biomass include direct burning, thermochemical and bio-chemical conversion processes. In the case of direct burning, since the biomass does not have very high heating value when compared with fossil energy fuels like coal, co-firing it along with coal is one of the better options. It has been tested at Coal and Biomass Energy Laboratory (CABEL) [1–3] of Texas A&M University. Bio-chemical methods include anaerobic digestion to produce bio gas (CH_4 rich mixtures) which can be used for heating applications. Thermo-chemical methods include torrefaction, pyrolysis and gasification. Torrefaction is carried out in the absence of oxygen at temperatures ranging between 200 °C and 300 °C. It results in the reduction of moisture and retains about 80–90% heat content of fuel. Pyrolysis is similar to torrefaction in terms of the environment used but it occurs at higher temperatures (above 300 °C). Pyrolysis results in the production of gases, liquid and solid combustibles (char), all of which can be utilized to recover energy. For pure pyrolysis of non-edible soy seeds at 33.9 kPa the percentage liquid, gas and char yields were measured to be 54.4%, 25.3% and 20.3% respectively [4]. On the other hand, gasification mainly produces combustible gases and liquids. Since dairy biomass has higher percentage of ash, gasification is one of the techniques which can be used to convert it into more usable form of energy. However, the heat value of gas mixture is only about

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Nomenclature

AR	as received
C	carbon
CAFO	concentrated animal feeding operation
CABEL	Coal and Biomass Energy Laboratory
CH_4	methane
C_2H_6	ethane
CO	carbon monoxide
CO_2	carbon dioxide
c_p	specific heat capacity at constant pressure (kJ/kg K)
DAF	dry ash free
DB	dairy biomass
ER	equivalence ratio
ER_M	modified equivalence ratio
FB	feedlot biomass
H_2	hydrogen
H_2O	water
H/C	hydrogen to carbon ratio
HHV	higher heating value (kJ/kg)
HHV_{ARfuel}	higher heating value of as received fuel (kJ/kg)
$HHV_{gas\ mix}$	higher heating value of gas mixture (kJ/kg)
kg	kilogram
kg/h	kilogram per hour
kJ	kilojoule
LAPCDB	low ash partially composted dairy biomass
MEET	multi stage enthalpy extraction
m_f	mass of fuel (kg)
m_g	mass of gas mixture (kg)
MS	mass spectrometer
N_2	Nitrogen
N/C	Nitrogen to carbon ratio
NO_2	nitrogen dioxide
NO_x	nitrogen oxides
O/C	oxygen to carbon ratio
$(O:F)_{stoich}$	stoichiometric oxygen fuel ratio
$(O:F)_{act}$	actual oxygen fuel ratio
Sep-sol	separated solid
S:F	steam fuel ratio
T_{peak}	peak temperature (k)
η_{gas}	gasification efficiency based on heating value

10–15% of heat value of natural gas due to dilution by nitrogen. In the present study, counter current fixed bed gasification facility in CABEL was used to study the effect of enriched air on the temperature profile and gas quality while gasifying dairy biomass. Enriched air mixture has higher oxygen concentration compared to that of air. Also, limited studies were done using carbon dioxide–oxygen mixtures as the gasifying medium, since carbon dioxide can be easily sequestered from the flue gas compared to nitrogen, and hence heat value can be enhanced.

2. Previous studies

A number of studies have been done to extract the available energy from wood [5,6] and municipal wastes (sewage sludge [7] and wastewater sludge [8]) using different gasification mediums such as air, steam, high temperature steam [5,8], pure oxygen [9] and enriched air having higher percentages of oxygen. Young and Pian [10] investigated the gasification of dairy wastes in a multistage enthalpy extraction technology (MEET) gasifier. MEET gasifier uses a high temperature preheated air in a reactor vessel to gasify the biomass into synthetic gas. Two different gasifier configurations were used in the study carried out by Young et al. The first one being a slagging type and the other being a nonslagging configuration. The different temperature ranges used were 1400 °C for the slagging mode and around 900 °C for the nonslagging operation. It was observed that the gross heating value of the gases produced increased while using high temperature air as the gasifying medium. Also both the gross and net gasification conversion efficiencies increased with increasing air preheat temperatures.

Raman et al. [11] studied the gasification of feedlot manure in a fluidized bed gasifier using the gas produced by the combustion of propane and air as the fluidization gas and silica sand as the bed material. The effect of reactor operating temperature on the product gas yields, composition and the higher heating value was studied and it was observed that the gas yields (CO, H_2, and CH_4) and the heating value increased with increase in the operating temperature.

Priyadarshan et al. [12] used a counter current fixed bed gasficiation facility to study the effect of particle size on the gasfication of litter biomass and high ash feedlot biomass. It was observed that the particle size did not have much effect on the gas composition and hence the heating value. However, high alkaline content in litter biomass resulted in agglomeration in the bed causing a reduction in peak temperature. During these gasification experiments the ash produced during gasification was not removed continuously from the reactor; thus, the peak temperature moved up continuously and it was not possible to reach steady state.

Gordillo and Annamalai [13] and Gordillo et al. [14] studied the gasification of dairy biomass and a mixture of dairy biomass with coal. Experiments were carried out for different equivalence ratios and steam–fuel ratios. From the experiments, it was observed that under fuel rich conditions (high equivalence ratio) and steam rich oxidizing source, the production of hydrogen was increased resulting in increased heating value.

Zhang [15] observed an increase in the heating value of the gases obtained by the gasification of loose biomass with oxygen enriched air in a fluidized bed gasifier. Gasification tests were carried out in a fluidized bed reactor using rice straw, rice husk, wheat straw, saw dust and combustible components in municipal wastes. Na et al. [9] studied the characteristics of oxygen-blown gasification for combustible wastes mixed with plastic and cellulose materials in a fixed bed updraft gasifier. They observed increased temperatures within the gasifier and decreased formation of char with an increase in oxygen flow rate.

Considering all the previous work it was observed that there were no studies on the gasification of cattle manure with enriched air mixture having higher oxygen concentration as well as using carbon dioxide oxygen mixture as the gasification medium.

3. Experimental facility

A 10 kW fixed bed gasification facility in Coal and Biomass Energy Laboratory, Texas A&M University was used for the current study. A schematic of the facility is shown in Fig. 1. It was constructed using a castable alumina refractory tube with an inner diameter of 13.9 cm (6 in.) and outer diameter of 24.5 cm (10 in.). The refractory tube is surrounded by an insulating blanket (9) of size 4.45 cm (1.75 in.) to minimize the heat losses. This entire set up is enclosed within a steel tube of inner diameter 34.3 cm (13.5 in.). The total height of the gasifier is 72 cm [3]. The facility has a continuous fuel feeding facility (11), well insulated reactor to prevent any major heat loss (9), perfectly sealed to prevent air leak in order to maintain fuel rich condition within the reactor,

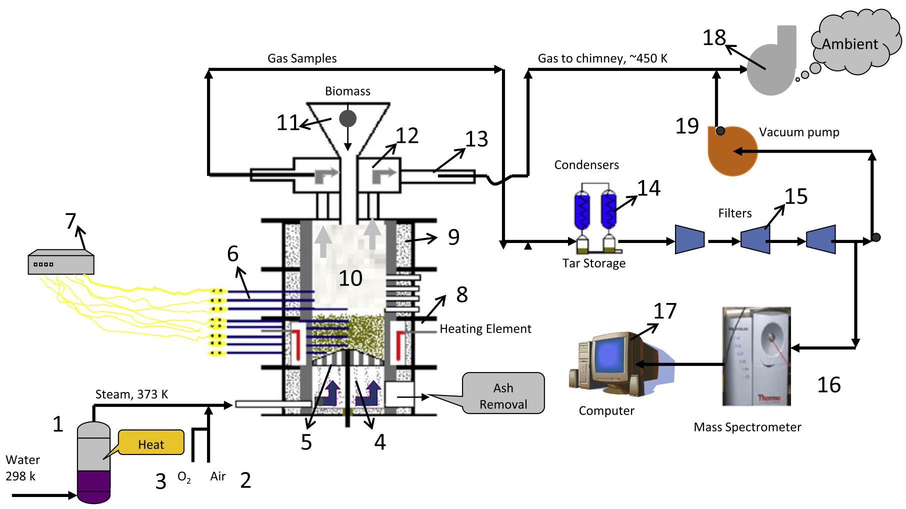

Fig. 1. 10 kW fixed bed gasification facility, adapted from Ref. [3].

air flow meters (2) to measure the amount of air entering the reactor, a steam generator to produce steam to study gasification in the presence of steam (1), a set of electrical heaters (8) to maintain a uniform temperature when non-adiabatic gasification is required, a grate with ¼" holes coupled with a pneumatic vibrator to remove the ash continuously during experimentation (5), suction pump (19) with gas filtration system to clean the gas produced during gasification, Thermo scientific Prolab mass spectrometer (16) along with computer (17) to analyze the clean gases coming out from the reactor followed by condensers (14) and filters (15), a suction fan (18) to drive out the gases produced and to maintain a slightly negative pressure within the reactor, K type thermocouples (6) present along the axis of the gasifier to measure the temperature, an Omega 8800 temperature recording system (7) which collects the data from the thermocouples and free board (10) above bed.

Variable area mass flow meters with an accuracy of +/−3% are used for measuring the air flow. When same flow meter was used for CO_2, corrections for different molecular weights as recommended by the manufacturer were made. Temperature measurements were done using K type thermocouples and recorded using Omega temperature recorder with an instrument uncertainty of +/−1.5 °C. Gas composition was measured using mass spectrometer which was calibrated using known gas mixtures once in 72 h to ensure accurate readings.

4. Procedure

The gasifier was initially preheated using a propane torch until the temperature at a height of 2 cm from the grate reached a steady temperature of 800 °C. Once the desired temperature was reached the torch was removed and the gasifier was sealed perfectly thereby preventing any air leak into the reactor. The pressure inside the reactor was maintained slightly below the atmospheric pressure using a suction fan. The fuel was added into the gasifier gradually until the bed height reached 17.8 cm (~7 in.). As the fuel was gasified, the ash produced was gradually discharged from the bed to the plenum and the bed height decreased. The bed was maintained at a constant height by adding fuel at regular time intervals. Air mixtures having higher percentage of oxygen were supplied to the reactor through the plenum (4). The temperature profile within the bed was monitored continuously using thermocouples located at different heights along the axis of the gasifier. The ash produced as a result of gasification was removed from the bed using a pneumatic vibrator coupled to the grate (5). Once the temperature profile reached a steady state, the gases were analyzed for their composition using a mass spectrometer (MS). A fraction of the gases produced during gasification was passed through a condensing system (14) which condensed out the condensables and then through a set of filters (15) to remove the particulates so that clean gas entered the MS without contaminating the MS. The same procedure was repeated for different equivalence ratio (ER) and steam fuel ratios (S:F). The total amount of tar produced during the experiments was not measured since the amount of volatile matter in LAPCDB is less when compared to wood based fuels. Furthermore, tar condenses in the top of the gasifier (lower temperature) and in the sample transport tube; thus, it was difficult to measure. However, Gordillo [3] using ultimate and proximate analyses characterized tar produced. Based on tar characterization, the empirical chemical formula was derived to be $CH_{2.01}N_{0.064}O_{0.48}S_{0.0017}$ with dry ash free heat value of 21,790 kJ/kg. Using atom conservation for the input fuel and steam, the chemical formula for tar and the measured gas composition, the yield of gases and tar was estimated. The tar yield was estimated to be 0.03–0.15 kg/SATP m^3 of gas produced for ER ranging from 2.1 to 4.2 with higher number corresponding to higher ER. More details are given in [3].

5. Results and discussion

5.1. Fuel properties

Low ash partially composted dairy biomass (LAPCDB) was used as the fuel for the present study. The ultimate and proximate

Table 1
Ultimate and proximate analysis of fuel sample, adapted from Ref. [3].

Dry loss%	25.26
Ash%	14.95
VM%	46.84
FC%	12.95
C%	35.27
H%	3.1
N%	1.9
O%	19.1
S%	0.42
HHV (kJ/kg)	12,844
DAF HHV (kJ/kg)	21,482
Dry HHV (kJ/kg)	17,185
Empirical formulae	$CH_{1.06}N_{0.047}O_{0.405}S_{0.0045}$

analysis of LAPCDB in storage condition is shown in Table 1. The fuel was obtained from the facility in Amarillo, Texas. Since the fuel was stored for 3 years, a change was observed in the fuel proximate analysis (ash and moisture percentage). Typically the moisture and ash contents change depending on duration of storage but the heat value on dry ash free basis remains almost constant [16]. Thus proximate analysis was conducted at the time of test. Moisture percentage of the samples in experimental condition was 13%. However the H/C, O/C and N/C nearly remained constant. Sweeten et al. [16,17] observed an increase in ash percentage and a corresponding decrease in combustibles on a dry basis with increase in composting time. The same trend was observed in the present study.

5.2. Biomass preparation

Properties of dairy biomass also depend on the surface from which the manure is collected. Biomass collected from concrete floor has lower ash content when compared to the one collected from soil surface because of collection technique disturbing the soil surface. The manure collected in concrete floors is first flushed out using a stream of water and the resulting fluid is then passed through a mechanical separator to remove the solids from the liquid. The liquid is then circulated to be used as lagoon water. LAPCDB separated solids (sep sol) are obtained using this collection technique [2].

For the current study, coarse ground samples of LAPCDB sep sol were obtained from Amarillo, Texas. Coarse ground samples were used because samples having lower particle size resulted in fuel entrainment and packed beds causing poor distribution of gasification medium within the reactor.

5.3. Experimental results

Equivalence ratio is typically used in USA to describe the degree of rich or lean mixture and is defined as ratio of stoichiometric air (A): fuel (F) to the actual A:F ratio in the mixture (or ratio of actual F:A to stoichiometric F:A ratio). Stoichiometric ratio (SR), typically used in EU, is defined as the inverse of ER i.e ratio of actual A:F to stoihiometric A:F ratio. Since enriched air mixture is used, the air (A) will be replaced with oxygen (O) in the above definitions. For all the experiments, the Equivalence ratio (ER) used was calculated using the following formula [18]:

$$\mathrm{ER} = \frac{(\mathrm{O}:\mathrm{F})_{\mathrm{stoich}}}{(\mathrm{O}:\mathrm{F})_{\mathrm{actual}}},\quad \mathrm{Rich}:\mathrm{ER} > 1;\quad \mathrm{Lean}:\mathrm{ER} < 1 \tag{1}$$

When steam is used along with air, steam fuel ratios (S:F) were calculated according to the amount of steam sent in to the amount of fuel and is expressed as below:

$$\mathrm{S}:\mathrm{F} = \frac{\text{kg of steam}}{\text{kg of fuel sent in}} \tag{2}$$

The steam which enters the reactor is in a superheated state at about 110 °C. Modified ER ($\mathrm{ER_M}$) was determined to take into account the total oxygen which enters the reactor in air and steam. During experiments, once the steady state was reached, the effects of various parameters on peak temperature, temperature profile and gas composition were studied.

5.3.1. Temperature profile

For the gasification experiments with higher oxygen percentages, at ER = 2.1 and S:F = 0, the temperature profiles obtained are plotted in Fig. 2. The peak temperatures obtained was comparable to the theoretical values obtained using B number also known as transfer number in combustion literature which is defined in equation (3) [18] (Fig. 3). Gordillo and Annamalai [13] compared the results for peak temperature with experimental data for air and steam mixture as oxidizing medium. Simplified combustion theory under diffusion control yields:

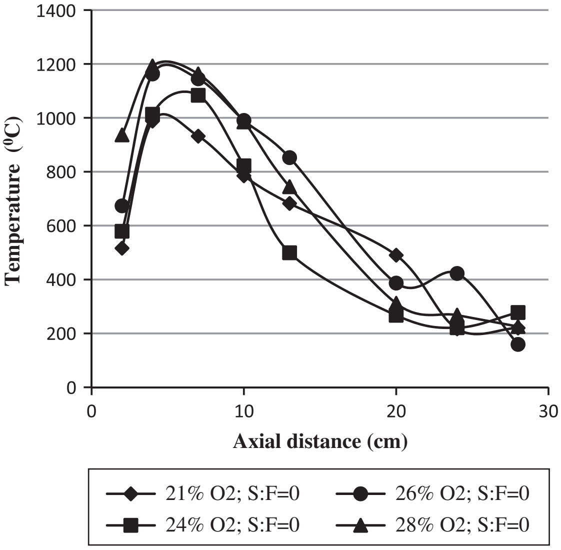

Fig. 2. Effect of oxygen percentage on temperature profile, ER = 2.1, S:F = 0.

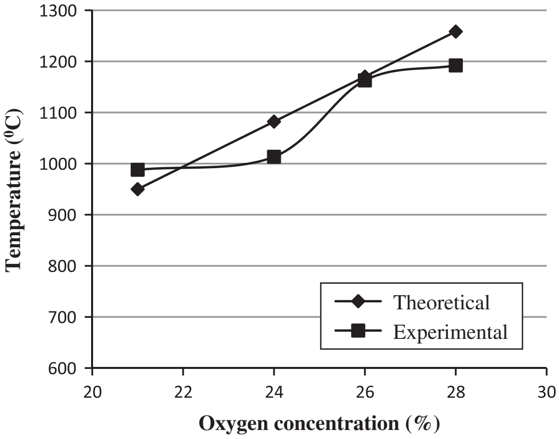

Fig. 3. Experimental peak temperature vs. theoretical peak temperature.

$$\frac{c_p(T_s - T_\infty)}{h_c} = \mathrm{B};\quad \mathrm{B} = \frac{Y_{\mathrm{O}_2}}{\nu_{\mathrm{O}_2}} \tag{3}$$

where T_s is the surface temperature of the particle (K), c_p is the specific heat of the mixture, Y_{O_2} is the mass fraction of the oxidizer, ν_{O_2} is stoichiometric oxygen for producing a mix of CO and CO_2 and its value is 1.33 for CO production, 2.667 for CO_2 production and h_c is the reaction enthalpy for the carbon to carbon monoxide reaction (9204 kJ/kg) [18,19]. From Fig. 2, it can be seen that the peak temperature obtained when using enriched air mixtures increased with increase in oxygen concentration. As the ER increases, the peak temperature was observed to decease. This is because, increased ER implies lesser oxygen entering the gasifier; therefore the gasification process occurs in a poor oxygen environment which favors the oxidation of C to produce CO.

Fig. 4 shows the steady temperature profile with and without steam at ER = 2.8. In the present study all the experiments involving steam were carried out for only one S:F which is 0.33 kg of steam per kg of as received fuel or 0.55 kg of steam per kg of dry

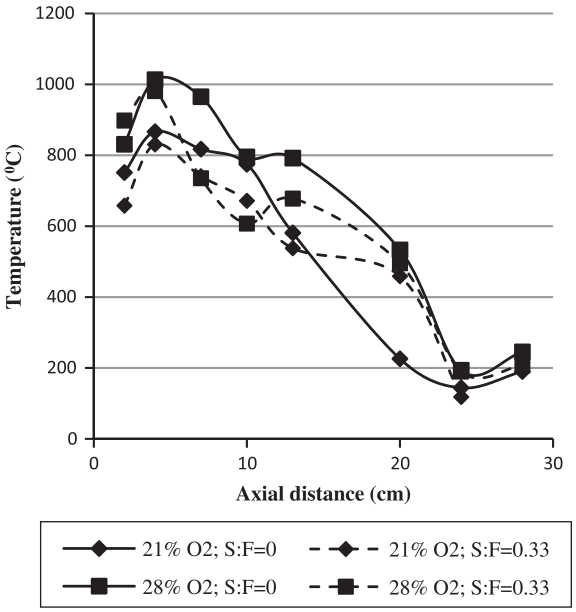

Fig. 4. Steady temperature profile, ER = 2.8, ER_M = 1.8.

ash free fuel. The temperature profiles had different slopes because of the variation in thermal diffusion and convection of the gasification medium (air or enriched air or air steam mixture) and the pore spaces through which the hot gases travel up along the bed through the available voids within the bed.

At ER = 2.8 (ER_M = 1.8) the peak temperature decreased with the addition of steam as it was expected to be; however, for gasification with 21% oxygen at ER = 4.2 (ER_M = 2.4) and S:F = 0.33 (Fig. 5), the peak temperature obtained was slightly higher than the peak temperature obtained for the case without steam. This may be due to (a) slight exothermic nature of the water gas shift reaction, (b) combustion of hydrogen within the oxidation and reduction zones, (c) cracking of steam into hydrogen and oxygen which in turn results in more oxygen available for oxidation, (d) increased mass flow (air flow and steam flow) into the reactor which in turn results in better diffusion of air within the bed and in turn better oxidation and hence higher temperature.

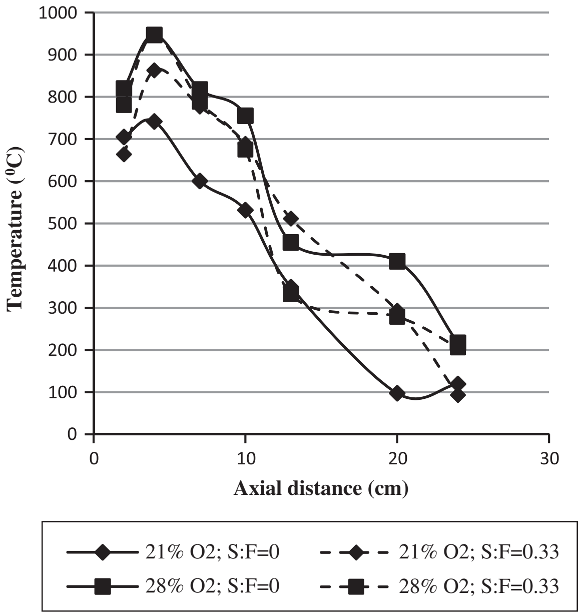

Fig. 5. Steady temperature profile, ER = 4.2, ER_M = 2.4.

Enriched air results in the presence of nitrogen in syn-gas which lowers the heat value of gases. Also, carbon dioxide (CO_2) can be separated easily from products compared to nitrogen (N_2) in the event CO_2 sequestration is necessary to enhance the heat values. Hence experiments were performed using carbon dioxide–oxygen mixture as the gasification medium instead of air. In this case, carbon dioxide is substituted for nitrogen in the air mixture. Also the carbon dioxide produced as a result of gasification can be separated and circulated again into the reactor at high temperatures (e.g. as cooling medium for gasifier) in order to increase the efficiency of the reactor and also to sustain the reaction within the gasifier. This in turn helps to reduce the amount of carbon dioxide released into the environment. CO_2 has a slightly higher specific heat (c_p) than N_2 at higher temperatures. Then c_p of the mixture of CO_2 and O_2 is higher than c_p of the mixture of N_2 and O_2. Hence, T_{peak}, using CO_2 instead of N_2, is expected to be low. This will also increase the upper limit on ER. The difference in peak temperatures can be observed in the temperature profiles (Fig. 6) obtained using carbon dioxide in the gasifying medium instead of nitrogen.

However, at higher oxygen percentages, the peak temperature obtained using carbon dioxide was almost similar to that of air. This may be explained as follows: as O_2 increases, T_{peak} is expected to increase which then drives the endothermic Boudouard reaction ($C + CO_2 \rightarrow 2CO$; ΔH_R = 14.42 MJ/kg). Further studies need to be performed in order to provide a better understanding of the various mechanisms taking place within the gasifier during CO_2:O_2 gasification.

5.3.2. Gas composition

For all the experiments, the gas composition was measured using a Thermo scientific Prolab mass spectrometer. Fig. 7 shows the gas composition obtained for enriched air gasification at ER = 2.1 and S:F = 0. The percentage of carbon dioxide produced increased with increased oxygen percentage due to higher oxygen concentration in the incoming gasification medium. It was accompanied by a decrease in carbon monoxide and an increased production of hydrogen. As discussed earlier, increasing O_2 increases the temperature which tends to favor the formation of smaller molecules in the gas mixture.

Table 2 shows the variation in gas composition for different equivalence ratios when using air as the gasifying medium with

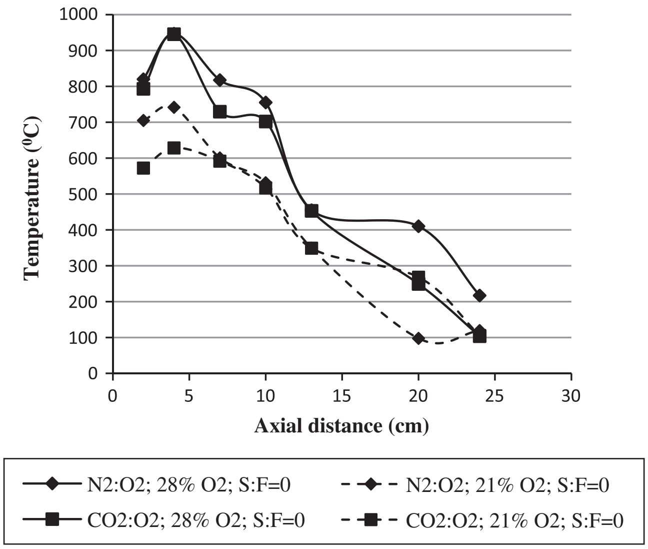

Fig. 6. Steady temperature profile, CO_2:O_2, ER = 4.2, S:F = 0.

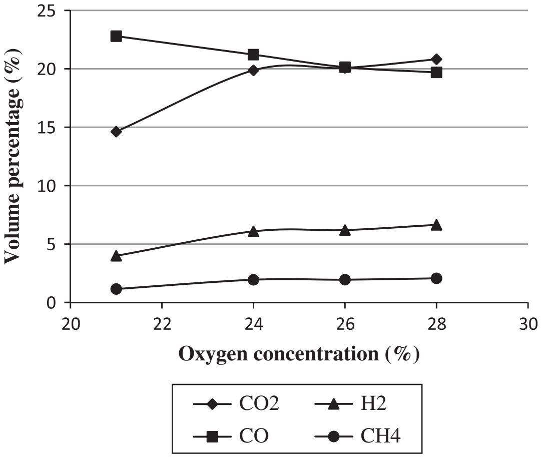

Fig. 7. Gas composition for enriched air gasification, ER = 2.1, S:F = 0.

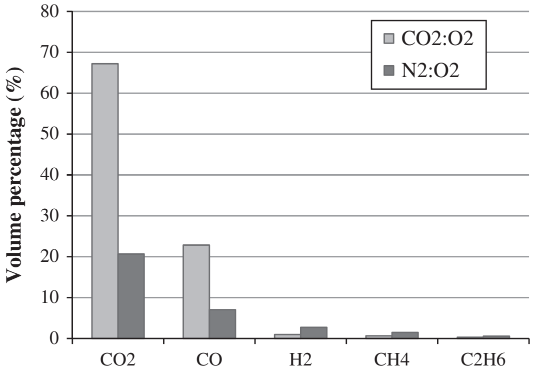

Fig. 8. Gas composition comparison, 21% oxygen, ER = 4.2, S:F = 0.

and without steam. The amount of hydrogen produced increases with introduction of steam into the gasification reactor. Also the presence of moisture in fuel can increase H_2 production. The trend observed was an increase in carbon dioxide and decrease in carbon monoxide with increased ER. When steam is added, it had the following effects: (i) physical and (ii) chemical. The physical effects include (i) increase of specific heat of mixture (c_{pmix}) due to higher c_p of H_2O (e.g. c_{pmix} for air = 1.08 kJ/(kg K) while for c_{pmix} for steam: air mixture = 1.14 kJ/(kg K) at 700 K) and (ii) reduction in oxygen mass fraction due to added H_2O with gasification medium. Both of these effects will decrease T_{peak}. The chemical effects include (a) reduction in rate of oxidation of C to CO due to reduced O_2 concentration, (b) promotion of steam carbon reaction, and (c) more production of H_2 and CO_2 but reduction of CO due to higher concentration of H_2O which promotes CO + H_2O reaction at same T_{peak}. While (a) and (b) result in decrease of T_{peak} the third effect i.e. CO + H_2O reaction can release heat resulting in rise of temperature. But this reaction is more likely downstream of peak temperature location since bulk gas flow opposes upstream diffusion of CO. Hence, generally T_{peak} decreases with addition of H_2O which is supported by the experimental data. When T_{peak} is decreased, generally T decreases throughout the bed indicating that CO + H_2O will favor more production of H_2 and reduction of CO if one assumes chemical equilibrium and this trend is also revealed in the experimental results. The gas composition obtained for experiments with 28% oxygen is also shown in Table 2. From the gas composition obtained it can be seen that CO production is enhanced at lower ER in the absence of steam due to higher T_{peak} at lower ER, which favor the oxidation of C to CO. However, with increase in ER, i.e. at ER = 4.2, the amount of carbon monoxide is lesser possibly due to the water gas shift reaction or increased peak temperatures which improves oxidation of C to CO_2.

Fig. 8 shows the comparison between the gas composition at 21% O_2 obtained for the gasification with air and carbon dioxide at ER = 4.2. Since carbon dioxide replaces nitrogen in the air the gases produced during gasification has a higher percentage of carbon dioxide which includes both carbon dioxide produced by oxidation of C and shift reaction as well as the carbon dioxide entering as the gasifying medium The decrease of H_2 can be explained using water gas shift reaction. The increased CO_2concentration will promote the formation of CO along with the reduction of H_2 at the same temperature based on the presumption of chemical equilibrium of water gas shift reaction.

5.3.3. Heating value

Variation of HHV with ER in the presence and absence of steam for the case of air (21% O_2) and enriched air mixtures (28% O_2) is shown in Table 3. The enriched-air medium results in gas with higher HHV. Since, the amount of hydrogen produced increases in the presence of steam, but the HHV based on mass is less even with H_2 due to lower molecular weight of H_2. For both air gasification and enriched-air gasification, we observe a decrease in HHV with ER. Table 3 also gives the HHV of the gas mixture with inerts (N_2 and CO_2) and without inerts (N_2 and CO_2) and these values are expressed in terms of percentage HHV of natural gas.

Typically the HHV of the gases increased from 2219 kJ/m^3 to 3479 kJ/m^3 when carbon dioxide–oxygen mixture is used for gasification instead of air at ER = 4.2 in the absence of steam. This is due to higher CO. Higher production of carbon monoxide may be due to higher concentration of carbon dioxide available for reaction by the Boudouard reaction. Hence the heating value of the resulting gas mixture is higher than those obtained using air as gasification medium.

5.3.4. Gasification efficiency

Nitrogen tracer method was developed to determine the heat based gasification efficiency from the percentage of nitrogen in the gases produced during gasification. The major assumption used in this method is that N_2 released from the fuel during gasification is negligible compared to N_2 from air used as the gasification medium. This is because LAPCDB has very low percentage of N which is 1.9% (0.019 kg/h), which is very low when compared to the amount of N_2 which enters the reactor along with air (1.9 kg/h at ER = 2.1

Table 2
Gas composition results for different parameters in volume percentage.

	21% ER = 2.1; SF = 0	21% ER = 2.8: SF = 0	21% ER = 4.2; SF = 0	21% ER = 2.8; ER$_M$ = 1.8; SF = 0.33	21% ER = 4.2; ER$_M$ = 2.4; SF = 0.33	28% ER = 2.1; SF = 0	28% ER = 2.8; SF = 0	28% ER = 4.2; SF = 0	28% ER = 2.8; ER$_M$ = 1.8; SF = 0.33	28% ER = 4.2; ER$_M$ = 2.4; SF = 0.33
CO_2	14.62	17.55	20.67	22.54	24.35	20.82	25.12	24.81	21.99	23.06
CO	22.79	15.39	7.04	7.83	4.64	19.69	17.47	11.6	19.91	10.91
H_2	3.99	4.13	2.74	9.89	8.58	6.64	3.66	3.52	11.85	10.2
N_2	55.54	58.15	62.73	52.73	55.55	47.52	50.43	53.75	41.52	53.2
CH_4	1.15	1.56	1.49	1.99	1.53	2.06	1.54	1.61	2.21	2
C_2H_6	0.48	0.57	0.58	0.55	0.47	0.77	0.64	0.55	0.69	0.59

Table 3
Heating value of the syn gas.

	21% ER = 2.1; SF = 0	21% ER = 2.8; SF = 0	21% ER = 4.2; SF = 0	21% ER = 2.8; ER_M = 1.8; SF = 0.33	21% ER = 4.2; ER_M = 2.4; SF = 0.33	28% ER = 2.1; SF = 0	28% ER = 2.8; SF = 0	28% ER = 4.2; SF = 0	28% ER = 2.8; ER_M = 1.8; SF = 0.33	28% ER = 4.2; ER_M = 2.4; SF = 0.33
HHV (kJ/kg)	3245	2699	1709	2766	2070	3648	2720	2205	4333	3002
HHV (kJ/N m^3)	4167	3470	2219	3401	2598	4670	3711	2922	5351	3860
HHV with N_2 & CO_2 (% CH_4)	10.52	8.76	5.6	8.58	6.56	11.79	9.37	7.38	13.51	9.74
HHV without N_2 & CO_2 (% CH_4)	37.01	40.47	47.29	42.36	43.07	40.41	40.19	42.69	39	41.11

and 0.7 kg/h at ER = 4.2). Thus nitrogen through fuel is neglected in estimating the gasification efficiency. From the concentration of nitrogen in the gases produced and the total amount of nitrogen entering the reactor along with air, the total dry moles of gas produced during gasification can be estimated using the following formula:

$$N_2(\text{Volume\%}) = \frac{N_2\,\frac{\text{mole}}{\text{h}}}{\frac{\text{dry gas moles}}{\text{h}}} \tag{4}$$

From the dry gas moles and molecular weight of gas mixture, gasification efficiency based on heating value of gas can be obtained using the formula below:

$$\eta_{\text{gas}} = \frac{m_{\text{gas}} * \text{HHV}_{\text{gas mix}}}{m_f * \text{HHV}_{\text{AR fuel}}} \tag{5}$$

From the nitrogen tracer method, it was observed that the total mass of gases produced decreases with increase in ER because of decrease in the amount of gasification medium supplied to the reactor and due to higher tar production at higher ER. Heat based gasification efficiency (η_{gas}) depends on the mass of gas produced. Hence at higher ER (η_{gas}) is low. From the calculations, it was obtained that η_{gas} at ER = 2.1 was 73% for air having 21% oxygen and it decreased to 17.33% at ER = 4.2. For enriched air gasification having 28% oxygen (η_{gas}) decreased from 66% at ER = 2.1 to 18% for ER = 4.2. For enriched air, the heat value of gases produced reached a maximum of 5351 kJ/N m^3 (13.5% of CH_4) at ER = 2.8 (ER_M = 1.8) and S:F = 0.33 with N_2 and CO_2 and 15,446 kJ/N m^3 (39% of CH_4) without N_2 and CO_2. For CO_2–O_2 mixture the corresponding values are 5220 kJ/N m^3 (13% of CH_4) at ER = 4.2 (72% CO_2–28% O_2) with CO_2 and 14,306 kJ/N m^3 (36% of CH_4) without CO_2 in the gas mixture.

6. Summary and conclusion

Experimental studies have been performed on low-ash, partially composted dairy biomass in an adiabatic, fixed-bed gasifier using different gasifying mediums such as air, enriched air having higher oxygen percentage in the presence and absence of steam and also with carbon dioxide–oxygen mixture. Lower ER and higher oxygen percentage in the gasifying medium results in higher peak temperature within the bed which can lead to ash melting and fouling. This hinders normal diffusion of the gasifying medium within the bed and in turn makes a steady temperature distribution impossible and hence there exists a lower limit on ER and upper limit on oxygen percentage. In the presence of steam, the peak temperature generally decreases as expected for most of the cases due to higher specific heat of steam and endothermic steam reforming reaction. This is expected to control the bed temperature below the ash melting temperature. The heating value of the gases produced decreases with increase in ER for both air and enriched air gasification mostly due to higher tar production at higher ER. Carbon dioxide–oxygen gasification in the presence of carbon dioxide instead of nitrogen can be used to get lower peak temperatures even with increased oxygen concentration within the reactor owing to higher specific heat of carbon dioxide when compared to that of nitrogen. Also, the carbon dioxide produced during gasification can be separated and re-circulated thereby reducing the emission of carbon dioxide into the environment. The CO_2 separation can lead to a higher heating value for the gases produced, and heat value of gases could be as high as 40% of CH_4.

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